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Energy-based assessment of ductile tearing in a thin sheet aluminium alloy

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Abstract

This paper deals with several issues in ductile tearing assessment. One of them is the contrasting of energy-based parameters, namely, the Essential Work of Fracture (EWF) [1], w_{et}, and the Energy Dissipation Rate (EDR) [2], R. We intend to answer the following questions: (i) Is there a reasonable correlation between w_{et} and R? (ii) Is there any correlation between their constituents? and, finally, (iii) Are the energy- and displacement-based characterizations of slant crack growth under uncontained yielding consistent with each other?

Plane stress tearing; energy dissipation rate; essential work of fracture; crack mouth opening angle; crack tip opening angle; aluminium alloy.

1. Introduction

To upgrade a new methodology for through-life assessment of internal cracks in plates and shells of metallic materials, we performed tensile tests of single-type specimens with different shapes and sizes of the Problem Domain (PD) shown in Fig. 1 and Table 1. This three-level procedure, called Unified Methodology (UM) of fracture investigation [3-5], can assess a tear crack continuously (from its nucleation up to complete fracture) or in a point-by-point manner depending on the application and service conditions. Focus is on comparing experimental results obtained with the use of two pairs of relatively simple test methods. These are the EWF and EDR methods and the UM-based tensile tests of the narrow and wide plates shown in Fig. 1c.

The main goal of this study is to demonstrate that the L1 and L2 methods (Table 1) might be attractive alternatives to the EWF and EDR methods, which are popular test procedures for thin-sheet materials. The L1 method aims at simplified assessment of the fracture initiation and onset of Steady State Tearing (SST) in a small MR(T) specimen (Fig.1c). Its horizontal edges are rigidly clamped and the PD has an open hole of a specific radius r_0 [6]. To be closer to the conventional tensile test procedure, the PD width $2W_0$ is taken equal to that of the standard S(T) specimen (Fig. 1a). The L2 method assesses tearing in MR(T) specimens with reasonably large dimensions

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$2W_0$ and $2H_0$. In addition, we tested M(T) specimens (Fig. 1d) having a notch with a well-defined geometry of its tips and DEN(T) specimens (Fig. 1b) having notches with widely different tip curvatures r_0 (see Table 1).

2. Material and Tests

The test material is aluminium alloy D16AT in as-received condition, having a form of 1.4 - 1.5mm thick sheets. All specimens were loaded very slowly under quasi-fixed grip conditions (with the rate 0.001 mm/s) in tension across the rolling direction of the sheets. The material behaviour was characterized by the following parameters: the elastic modulus E = 67.7 GPa, Poisson's ratio $\nu = 0.32$, the 0.2% offset yield strength σ_Y = 300MPa, and the ultimate tensile strength σ_{UTS} = 446MPa. In specimens with the stress raiser tips of radius r_0 = 1mm (Table 1), the fracture process always occurred by slant cracking along the 0x axis in the plane inclined at 45° to the sheet surfaces.

The displacements v(m), u(n), v(M), and u(N) of the so-called extreme points m, n on the inner and M, N on the outer PD boundaries are measured as functions of the load P applied along the 0y axis (Fig. 1). These test records are used to relate changes in the global geometry of the inner and outer PD boundaries. All specimens were loaded without guide plates preventing the out-of-plane displacement (buckling due to compressive T-stress). The MR(T)-1.0-1.0 and M(T)-1.0-1.0 specimens buckled at c > 20mm (Fig. 2a). Because of a relatively small ligament length-to-thickness ratio, the characteristics of plastic flow and cracking in specimens of other types are not affected by buckling. The post-test values of the Crack Opening Spacing (COS - $2s_n$), Crack Mouth Opening Angle (CMOA - η_n), and Crack Tip Opening Angle (CTOA - ψ_n) were measured using a fully fractured specimen (Fig. 3a) [5].

3. Results and Discussion

In Figs. 2-4 only a small part of the available results is displayed due to a space limitation. By comparing the SST portion of crack profiles ($n1$-nb in Fig. 3a) with the related data in Fig 2a, one can see that the SST stage and the next stage (nb-f) of Tail End Tearing (TET) are both affected by buckling. Additionally, the TET cracks interact with the stress-free boundaries ($x = \pm W_0$ in Fig. 1). The L2 method should ensure—and indeed it does (see data for MR(T)-1.0-1.0 specimens in Fig. 2b)—a near coincidence between the net-section stress σ_N values at the tear crack formation, σ_i, and at the SST onset, σ_{d1}. Here, the index d denotes a through-life fracture curve reflecting

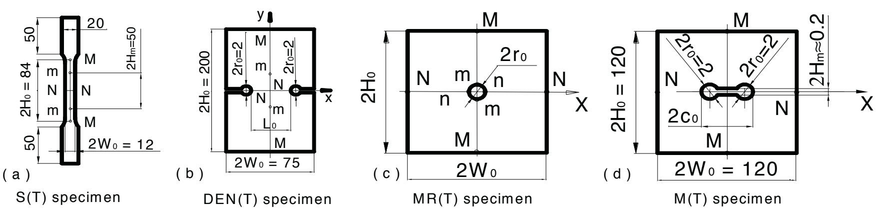

Fig. 1. Geometry and code of tensile test specimens used in this study (all dimensions are in mm).

Table 1. Principal dimensions of specimens

Specimen code*	$2W_0$ (mm)	$2H_0$ (mm)	$2H_m$ (mm)	r_0 (mm)	$2c_0$, L_0 (mm)	Procedure
S(T) - 7.0 - 0.1	12	84	50	0	0	Standard tensile test
MR(T) – 1.0 – 0.1	12	12	2	1	2	L1 method
MR(T) – 1.0 – 1.0	120	120	2	1	2	L2 and EDR methods
M(T) – 1.0 – 1.0	120	120	0.2	1	Variable	EDR method
DEN(T) – 2.67 – 0.63	75	200	45	0.03	Variable	EWF method
DEN(T) – 2.67 – 0.63	75	200	45	1	Variable	Modified EWF method

* The numerical values denote the shape, $\lambda = (H_0 / W_0)$, and size, $\mu = (W_0 / W_0^{BSE})$, ratios, respectively. In this work we take $2W_0^{BSE}$ = 120 mm.

the incubation of localized damage during step-wise cracking [5]. In M(T) specimens with elongated notches a tear crack propagates under an increasing level of net-section stress. The results in question lead us to the following important conclusions. The change of the rate R_t within the SST range (*t1-tb* in Fig. 3b) is due to buckling effects and also the variation in the distances between moving crack tips and a highly restrained plane ($x = 0$ in Fig. 1c), on the one hand, and free-to-move surfaces ($x = \pm W_0$), on the other hand. It was shown that the short centre cracks restrained by biaxial loading in tension, unlike the long ones, absorb plastic deformation without sliding along diagonal shear bands [7]. Another conclusion concerning tensile tests of centre-cracked specimens is that the commonly used size requirement, $c_0 = 0.3 \div 0.4\ W_0$, leaves by itself the SST stage out of a reasonable fracture analysis.

Among the clearly distinct constituents of the work of external loads [4] we consider only specific values of the total work, w_{tot}, and the work of fracture, w_f. The latter parameter is associated with an area under the softening portion of the test record (*if* in Fig. 4a). Thus it averages (in an approximate manner) the energy exchanges during the SST and TET stages. According to the EWF method [1], we tested specimens with different ligament lengths L_0

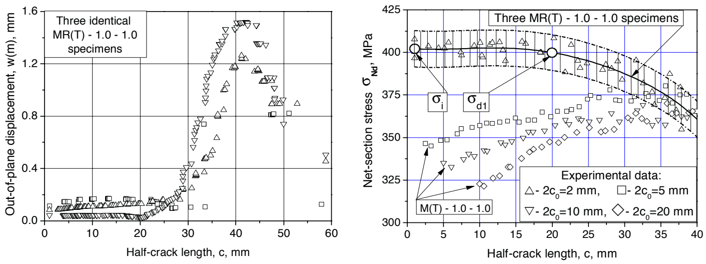

Fig. 2. Experimental data for specimens tested without unloading-reloading cycles (a) and diagrams for specimens with stress raisers of different lengths $2c_0$ (b). The SST stage of crack growth starts at $c \approx 20$ mm and ends at $c \approx 40$ mm.

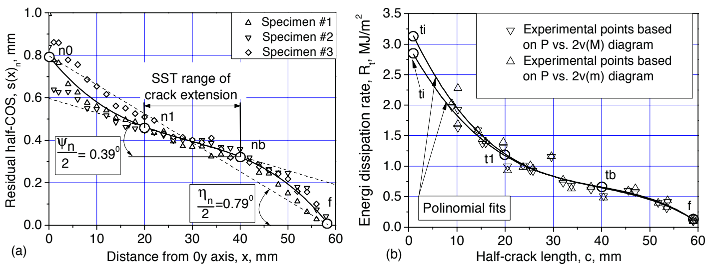

Fig. 3. One-quarters of crack profiles in fully fractured MR(T)-1.0-1.0 specimens (a) and the energy dissipation rates R_t at the instants t of fracture termination for the same set of specimens tested with *unloading-crack extension-reloading* cycles (b).

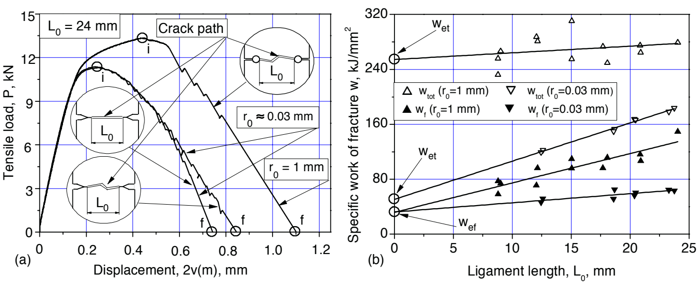

Fig. 4. Typical test records for three DEN(T) specimens (a) and linear fits of data for specimens with different L_0 (b).

and constructed linear plots shown in Fig. 4b. The nearly coinciding values w_{ef} =31.9 and 32.4 kJ/m^2 were obtained on DEN(T) specimens with r_0 = 1 and 0.03mm, respectively. They characterize an interaction of two crack tips approaching the highly restrained plane (0*y* in Fig. 1b). Apparently, this is the main reason why the w_{ef} values are by an order of magnitude smaller than the rate R_f = 250kJ/m^2 (Fig 3b) corresponding to the instant *f* of intersection of the free-to-move boundaries by the moving crack tips.

In the UM a combined characterization of tearing involves the following very simple relationships:

$$A_{n\psi} = (2W_0 - c_{n1} - c_{nb})\,\sigma_i\ tg\,(\psi_n / 2) \quad \text{and} \quad A_{n\eta} = W_0\,\sigma_i\ tg\,(\eta_n / 2),$$

where ψ_n, η_n are the angles shown in Fig 3a and $A_{n\psi}$, $A_{n\eta}$ are the specific work of fracture averaged over the SST range of crack growth and over the specimen width, respectively. For MR(T)-1.0-1.0 specimens tested with and without unloading-reloading cycles (L2 method), the above parameters take the values: σ_i = 389 and 403MPa; ψ_n = 0.78 and 1.28 degrees; η_n = 1.58 and 1.78 degrees; $A_{n\psi}$ = 159 and 270kJ/m^2, and $A_{n\eta}$ = 322 and 376kJ/m^2, respectively. For MR(T)-1.0-0.1 specimens tested without unloading-reloading cycles (L1 method), these parameters are as follows: σ_i = 415MPa, ψ_n = 3.46 degrees, η_n = 3.94 degrees, $A_{n\psi}$ = 75 kJ/m^2, and $A_{n\eta}$ = 86 kJ/m^2.

On the whole the results of this and previous studies [3-5] are contradictory to the commonly accepted statement [8]: "…the constraint effect in plane stress specimens is negligible". One can see that a single-parameter assessment of plane stress tearing in terms of the σ_i stress is preferable over ψ_n, η_n, $A_{n\psi}$, $A_{n\eta}$, w_{ef}, w_{et}, and also over the values of energy dissipation rate R_{ti}, R_{t1}, R_{tb}, and R_f shown in Fig. 3b. Its main advantage is a low sensitivity to the variation of the shape λ and size μ ratios of specimens, as can be seen from the results presented here and elsewhere [9]. The stress σ_i is of significance as an upper bound characteristic of a material's resistance to the formation of a tear crack near a free surface of constant curvature. The ratio of yield stress to crack nucleation stress, σ_Y / σ_i, may also be used in a simplified structural integrity analysis as an index of strain hardening effects in the assessment of fracture instability. The use of such characteristics as w_{ef}, w_{et}, $A_{n\psi}$, $A_{n\eta}$, and R_f in defect tolerance calculations may lead to unduly conservative predictions of crack instability events.

As to the three questions listed in Abstract, the following conclusions are pertinent: (i) When defined using the DEN(T) specimens with r_0 = 1mm, the essential total work w_{et} = 254.4kJ/m^2 nearly coincides with the rate R_f = 250kJ/m^2; (ii) There are no correlations between the essential work of fracture w_{ef} and the values of $A_{n\psi}$, $A_{n\eta}$, and R_t; (iii) Yes, they are consistent due to the shape similarity of the crack profiles and polynomial fits in Fig. 3. This experimental fact may be treated as a strong confirmation of the UM-based approach to coupling crack profile parameters with energetic parameters of plane stress tearing. Finally, the results of this and other studies [3-6,9] demonstrate that the UM is general enough to encompass a fairly broad range of fracture mechanics problems.

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